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Bio-inspired panel design for thermal management

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Abstract

Based in the fact that one of the most imperative action lines regarding the sustainability of manufactured products and services is the management of the total energy consumption, we design a thermal management device inspired in the polar bear's hair that consist of hollow cylinders, such that exposed to direct solar radiation shows a good performance as a thermal insulator. We conducted experimental measurements of temperature in a closed system exposed to direct solar radiation and observed that the temperature in the bio-inspired panel was at least 20% lower than the one registered in the surroundings. By means of numerical simulations we additionally show how the panel could be useful to improve the heat exchange exploiting the convection phenomena when varying the geometry of the proposal.

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Keywords: thermal management; bio-inspired design; insulated panel

1. Introduction

According to data provided by the United States Energy Information Administration (EIA), buildings are responsible of the consumption of about 49% of primary energy, in addition buildings emits approximately 57% of

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the greenhouse gases into the USA territory [1]. In China, the percentage of energy spent by buildings ranges 25-40% of the total consumption of the country [2]. Buildings and houses are designed and built in order to provide comfortable environments to human beings. Particularly in extreme climates, this comfort is strongly related to the thermal performance in closed rooms and it can be controlled either by mechanical heating, or air-conditioning systems as needed. All these systems are associated with energy consumption [3]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the European Committee for Standardization (CEN) are two of the organizations that have established different parameters and requirements related to human bein g's comfort levels for indoor facilities [4, 5]; most of the local regulations of different countries regarding energy performance are based on these references. Thermal insulation is one of the most feasible strategies used worldwide in order to achieve improved energy efficiency and specific comfort levels, especially in buildings and dwellings [3]. Different insulating materials have been widely used in order to reduce the energy requirements of heating and cooling systems; this reduction can be measured in environmental and economic savings [3]. For all the aforementioned, it is of capital importance to develop and improve the efficiency of thermal insulators since the correct usage of this building supplements leads to both, environmental and economic savings due to the indoor thermal performance upturn.

The frequently used materials as thermal insulators generally include air due to its low heat conductivity [6]. Traditionally, different geometric interconnected structures are used to prevent the movement of the air within the panel, such structures can be porous-like and others exploit fibers or polymeric materials. In accordance with Thorsell [7], "When the air is motionless, heat is transferred by conduction and radiation within the gas and the skeleton, or fibers, while if the air is allowed to move the convective mode of heat transfer gradually replaces that of conduction with a higher thermal conductivity as the result". Some of the techniques used to achieve thermal conductivity near the value of still air are among others, the replacement of air by an alternative gas, the addition of materials capable of absorb or scatter radiation, the evacuation of the encompassed air into the panel (vacuum) and finally a combination of all these techniques. The latter is intended to control one or several thermal transport mechanisms such as conduction, convection and radiation [7].

On the other hand *Biomimicry*, from the Greek *bios*, life and *mimesis*, imitation, is the study of the nature's models and their imitation; it also takes inspiration from these designs and processes to solve human problems [8]. Biomimicry analyzes nature's best ideas and adapts them for human use. A successful example of such adaptations is given in a mid-rice building designed by Architect Mick Pearce named *Eastgate Centre* which is placed in Harare, Zimbabwe and serves as the country's largest office and shopping complex. The building uses innovative passive environmental systems, modeled by imitating the way termites construct their nest. According to Pearce, due to this *biomimicryed* design, the air-conditioning system for this building uses 35% less energy than conventional buildings in the city [9]. In this research, we utilized some concepts from biomimicry to issue the term *Bio-inspired design*, in this context we decided to take some ideas from nature in order to implement them into the design and construction of a thermal insulating panel at laboratory level.

The *bio-inspired design* was based on polar bear's hair, because this animal has develop the ability of surviving in extreme cold climates where temperatures varies from -70° C to -40°C. The hair looks white, but actually it is transparent. This peculiarity helps reflect solar light in order to increase the temperature near the skin of the animal. Each individual strand has a geometry of a hollow cylinder which leads to enclosure certain amount of air into the hair, the same occurs between each fiber, this principle (enclosure air), makes that traditional thermal insulating materials can show its desired thermal behavior.

The geometric proposal for the design of the thermal insulating panel presented herein (that will be further explained in the subsequent sections), it is based on the idea of using a hollow tube filled with air in order to produce convective movements of the gas (air) for the reduction of the thermal conductivity of the whole assembly.

2. Designing the insulating panel

The insulating panel is modeled as a structure with different layers; the intermediate layer is a set of hollow tubes that play an import role in controlling thermic variables of the air chamber that is confined inside the panel. We include hollow cylinders to control the convective motion of the air through the panel. Furthermore we place the cylinders in a slanted position from the horizontal, the latter in order to assure air movements due to temperature gradients. The proposed geometry is shown in Fig. 1 where the array of cylinders is placed at a slant of almost 70 degrees respect to positive X axis; the following row has an angle of 113 degrees from the same axis and so on. According to previous researches [10, 11, 12], the efficiency of the movement of the air is strongly related to the tilt of the cylinders. When the hollow cylinder has an angle of 90 degrees respect to the horizontal, the convection movement of air due to temperature gradients becomes null. The effectiveness of the thermal insulation produced by an array of hollow cylinders that holds a fluid, depends on various variables: the aspect ratio (cylinder diameter divided by its length), the tilt angle, the fluid content in the tubes, the material composition of the panel and the total space where the panel is placed to work as desired, i.e. the thermodynamic surroundings.

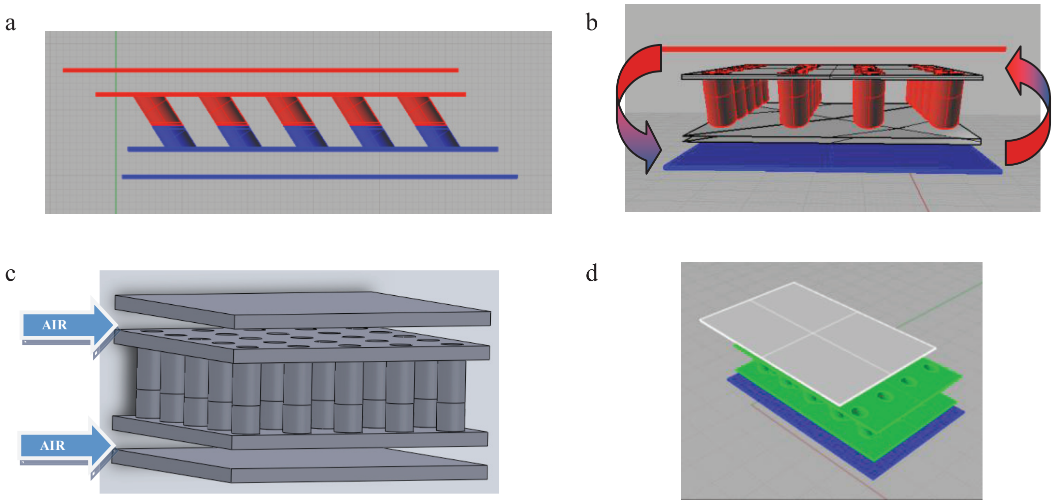

Fig. 1. (a) Transverse section of the assembly of insulating panel, the angle between the cylinders row and the horizontal is 113°; (b) 3D view of the proposed panel, it shows the scheme of the convective movement of air; (c) Rendered 3D view of the panel into the box that defines its thermodynamic surroundings; (d) The actual panel, the white colored box delimits its surroundings.

The experimental panel was constructed using acrylic tubes of 14 mm and 12 mm, external and internal diameter respectively. The cylinders were fixed on their upper and lower sides using cardboard perforated plates. This array was enclosed in a box to control and define the thermodynamic surroundings of the closed system.

3. The Experiment

The closed system was placed in a glass dome and exposed directly to the sun light in a very shiny day of May 2014 located at Toluca, in central Mexico; as a consequence, all the air outside the system (the environment) was considered as the heat source. In order to verify the effectiveness of the panel, we measured the temperature of the air outside the box (the heat source), and the temperature of the air confided in the system. The experiment started at 10:30 a.m., and 10 measurements of the local air temperature were conducted using a Traceable® RTD Platinum Thermometer in a twelve hour time lap, as reported in Table 1.

Table 1. Temperatures measured during the experiment conducted in a sunny day.

Hour	Weather condition	Temperature outside the system (°C)	Temperature inside the system (°C)
10:30	Shiny	21.3	20.7
11:00	Shiny	31.9	23.1
11:30	Shiny	34.7	24.9
12:00	Shiny	37.0	26.3
12:30	Shiny	38.3	28.2
14:00	Shiny	37.3	29.5
16:00	Cloudy	31.7	30.8
17:30	Cloudy	24.9	28.4
19:30	Cloudy	21.9	24.3
23:00	Cloudy	21.3	20.7

4. Simulation using a multi-physics finite element model

Since the experimental setup considered a closed system we performed a simulation to analyze the hydrodynamic behavior of the air passing through an individual cylinder, the appearance of convection inside the cylinder would be an indicative of heat transfer control through-out the system. The simulations where made using the Heat Transfer Module of COMSOL® Multiphysics [13]. The first step considered a simulation of an air chamber exposed to a heat source, we modeled the constant temperature gradient with fixed lateral boundary conditions. The convection is naturally induced as the result of the coupled phenomena, namely, a force induced by confinement and an opposite force resulting from the thermal gradient force antiparallel to the gravity.

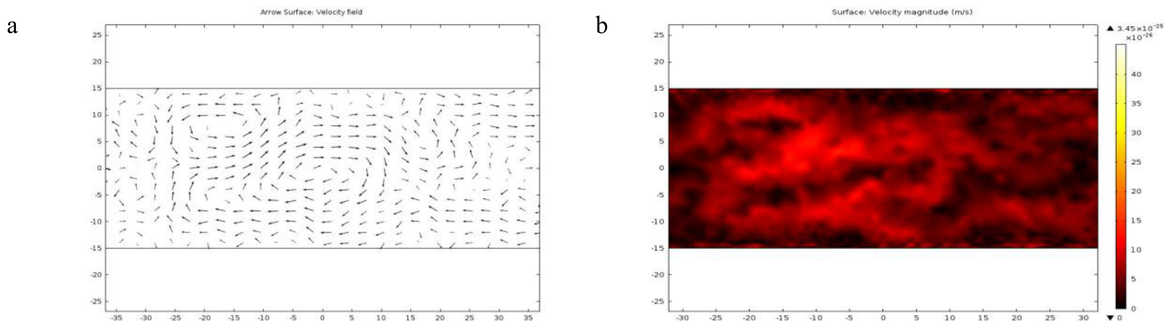

Fig. 2. Dynamics of the cross section behavior for an isotropic air volume, submitted to a constant vertical temperature gradient of 12 degrees, while the lateral boundary conditions are fixed. (a) Vector representation of the velocity field, (b) Colored representation for the velocity field values.

As shown in Fig. 2, the vector representation shows the convection cells that arise due to thermal and confinement forces. The simulation conditions were as follows: a rectangular cross section of 30 mm x 90 mm for the air volume modeled. The constant temperature gradient of 12ºC is achieved by setting the upper edge to a temperature of 35°C and the lower one to 23°C; while the lateral boundary conditions are fixed.

The second stage required adding the cylinder; since it is a 2D simulation such addition only includes the cylinder walls as a pair of slanted lines with a constant width and length, the experimental data is taken into account for these values. We show the comparison between three representative angles. The first one corresponds to the appearance of early stages of convection in the presence of the cylinder, this occurred when the tilt is almost 60 degrees. This is shown in Fig. 3, where we recreate the same thermal, confinement and external boundary conditions as for the simple air chamber. The cylinder's walls play the role of obstacles for developing convection in the middle of the system, as shown by the central area of Fig. 2(a).

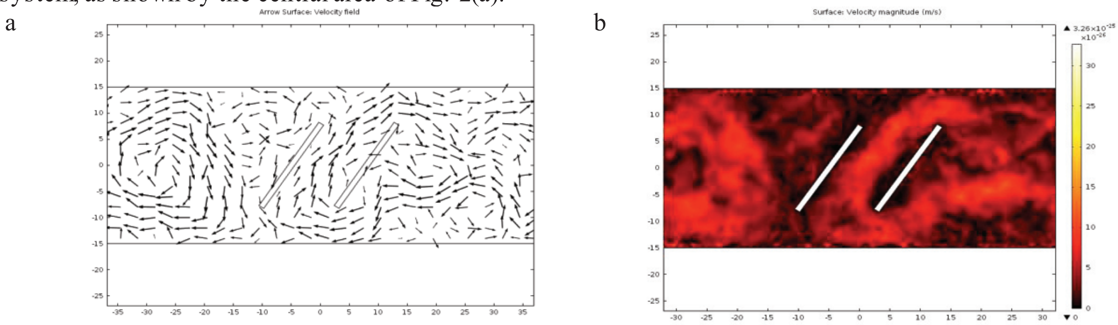

Fig. 3. Dynamics of the cross section behavior for an isotropic air volume surrounding the walls of a single cylinder located at the center of the system. Early stages of convection appear for a tilt of almost 60 degrees. The system is again submitted to a constant vertical temperature gradient of 12 degrees, while the lateral boundary conditions are fixed. (a) Vector representation of the velocity field, (b) Colored representation for the velocity field values

The array of vectors on the right hand side of Fig. 3 represents the velocity field of the air surrounding the walls; only one complete convection-like vortex is obtained opposed to the ones that appear without obstacles. The graph on the right hand side of the same figure represents colored visualization of the velocity field.

When increasing the slope of the cylinder to almost 70 degrees the convection is controlled and increased, showing convection-like vortex around each side of the wall and outside the cylinder, given by figure 4; hence the thermal insulation is more controlled and will yield to an efficient panel design.

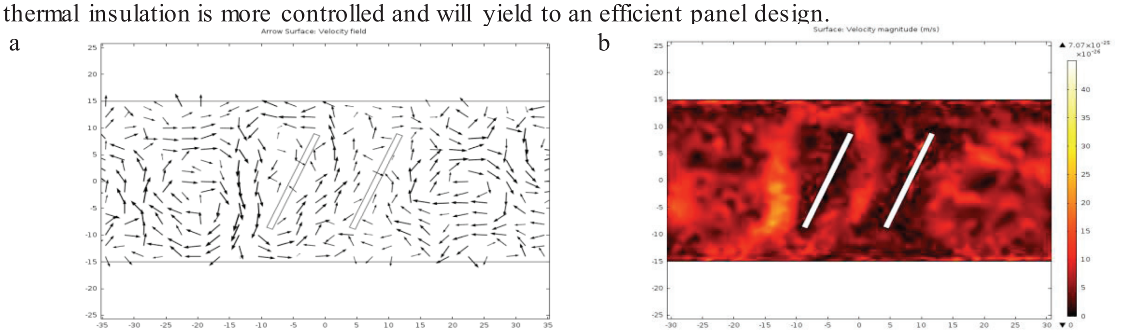

Fig. 4. Dynamics of the cross section behavior for an isotropic air volume surrounding the walls of a single cylinder located at the center of the system. Convection appears for a tilt of almost 70 degrees, yielding to an efficient control of temperature. The system is again submitted to a constant vertical temperature gradient of 12 degrees, while the lateral boundary conditions are fixed (a) Vector representation of the velocity field, (b) Colored representation for the velocity field values.

For the last simulation we considered another increase of ten degrees in the slope of the cylinder walls, and maintained the other thermodynamic parameters. Thus in Fig. 5, the simulation shows the decay of convection-like vortexes and diminishes the velocity of the air inside the structure; this would yield to an inefficient temperature control by means of the diminishing the air circulation through the cylinder. Again, the left hand side of Fig. 5 represents the vector velocity field and the right hand side the colored insight phenomena.

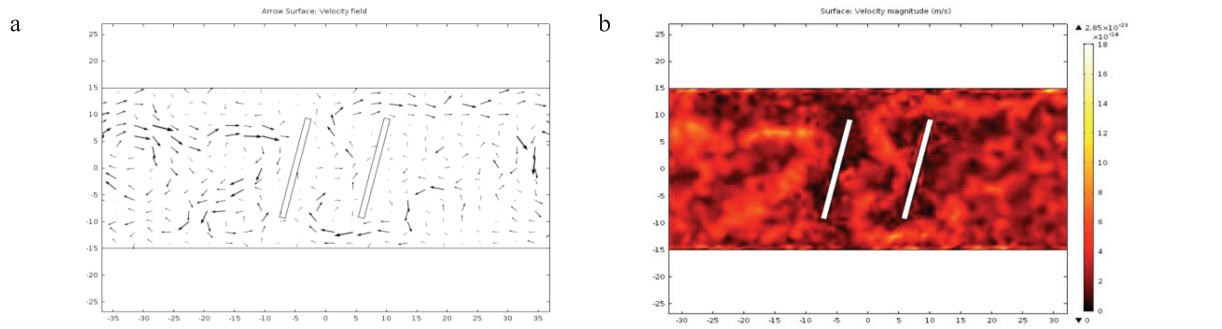

Fig. 5. Dynamics of the cross section behavior for an isotropic air volume surrounding the walls of a single cylinder located at the center of the system. Convection diminishes for a tilt of almost 80 degrees, which represents an inefficient temperature control. The system is again submitted to a constant vertical temperature gradient of 12 degrees, while the lateral boundary conditions are fixed. (a) Vector representation of the velocity field. (b) Colored representation for the velocity field values.

5. Discussion

The closed system was placed into a glass dome and exposed directly to the sun light in a very shiny spring day; as a consequence, all the air outside the system, i.e. the sun radiation was considered as the heat source. In order to verify the effectiveness of the panel, we measured the temperature of the air outside the box (the heat source), and we observed that under these conditions, the designed panel was useful as an insulator; on the other hand, the numerical simulation leads to the observation that under appropriate changes in the geometry, a thermal convection is established such that the device is more suitable for thermal management purposes.

Conclusions

The design herein presented was inspired by the thermo-regulation of a living organism; leading to a proposal that yields to a good performance as a thermal insulator panel. On the other hand, the numerical simulation shows how the cylinders can be suitably included to manage the convection phenomena leading to the heat transfer control of the air chamber for a variety of different applications, such as thermal insulation or a heat exchanger, among others i.e. our design is useful as a thermal management device.

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